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Life cycle analysis for future photovoltaic systems using hybrid solar cells

B. Azzopardi *, J. Mutale

The University of Manchester UK

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ABSTRACT

Global climate change concerns have lead to growing demand for renewable energy sources (RES). However the viability of these sources is critically dependent on environmental, economic and technological considerations. This paper focuses on the environmental aspect of future photovoltaic (PV) systems which are assessed through life cycle analysis (LCA). Previous LCA studies on commercially available PV systems are reviewed. The sustainable evaluation methods used in these studies are also discussed. These methods are applied to the hybrid quantum dot (QD)-based solar cells currently under development within a project between the University of Manchester and Imperial College London. The aim of this project is to develop affordable solar cells with efficiencies up to 10% for micro-generation applications. Presently hybrid QD-based solar cells are not commercially fabricated; therefore the study is mostly based on very small laboratory-scale production. For easy comparability 10% conversion efficiency and 25 years lifetime are initially assumed. Lower conversion efficiencies and shorter lifetimes likely to initially characterise emerging PV technologies such as the hybrid QD-based solar cells are discussed. Comparable criteria for sustainability of electricity-generating systems namely net energy ratio (NER), energy pay-back time (EPB-T) and CO_2 emissions per unit generated during lifetime are found to be lower than current commercially available PV modules.

Contents

1. Introduction

A vast number of life cycle analysis (LCA) studies on silicon-based (Si) photovoltaic (PV) modules have been presented in the scientific literature. Other non-Si based PV LCA studies have also been dealt with to some extent. Table 1 summarises the results of the most cited PV LCA studies since 1976. However, so far there are no published LCA studies on non-silicon-based hybrid quantum dot (QD)-based solar cells because no industrial fabrication processes have lead to stable long lifetime solar cells.

The development of sustainable technologies requires an overall evaluation of the product's environmental impacts and benefits. Solar cells currently on the market have undergone these environmental evaluations to be classified as sustainable sources of energy. Most of the studies were concerned with production processes; and their environmental impact assessment was commonly performed from cradle to gate. The environmental burdens during production are compensated during the utilisation phase due to low environmental impacts of renewable electricity generation.

* Corresponding author. Tel.: +44 0 161 306 8721; fax: +44 0 161 306 4820.
E-mail address: brian.azzopardi@postgrad.manchester.ac.uk (B. Azzopardi).

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Table 1
Summary of PV LCA studies.

Author	Year	PV technology	Some assumptions				NER	EPB-T	gCO_2/kWh
			PR	η%	Lifetime (years)	BOS			
Hunt	1976							12	
Hyne et al.	1991	CulnSe2		10	20			0.83–1.42	
Palz et al.	1991	mc-Si and a-Si	0.7	12 and 6				2.1 and 1.2	
Alsema	1996	mc-Si and a-Si						4.0 and 4.5	
Keoleian et al.	1997	a-Si		5	10	Y	1.34	7.4	
Kato et al.	1997	mc-Si	0.8			Y		15.5–11–4	91–65–21
Dones et al.	1998	mc-Si and sc-Si		14–16.5	30	Y			189–114
Kato et al.	1998	sc-Si/mc-Si/a-Si	0.8	12.2/11.6/8	20	Y		11.8/2.4/2.1	83/20/17
Frankl et al.	1998	sc-Si	0.9	11.2	25	Y		9	200
Alsema et al.	2000	mc-Si and a-Si	0.8	13.0 and 7.0	30	Y		3–4 and 2.5–4	60 and 50
Bossert et al.	2000	mc-Si		16–13.5				4.1–2.3	
		a-Si a-(Si, Ge):H		10				1.9–3.0	
		Thin-film Si		14				4.7	
		Cu(In,Ga)(Se,S)2		12				1.8–1.3	
		CdTe		10				0.9–0.5	
		Dye sensitised		8				1	
Knapp et al.	2001	sc-Si	0.8		30			4.1	
		CIS						2.2	
Greijer et al.	2001	Dye sensitised		7.0/12/9.0	20				19/22/25
Meijer et al.	2003	InGaP/mc-Si		25				5.3	
		InGaP						6.3	
		mc-Si						3.5	
Jungbluth et al.	2004/5	c-Si (sc/mc)		14.8–17.5	30			3.0–6.0	39–110
Peharz et al	2005	Con III-V multi-jun		26		Y		0.67	
Alsema et al.	2006	mc-Si	0.8	13.2	30	Y		1.8	32.5
Fthenakis et al.	2006	mc-Si	0.8	13.2	30	Y		2.2	37
		CdTe	0.8	8.0/9.0	30			1.0/1.1	21/25–18
Veltkamp et al	2006	Dye sensitised	0.8	8				1.3–0.8-0.6	20–120
SENSE project Shibasaki	2006	a-Si	0.8					1.25	
		CIGS						1.3	
Raugei et al.	2007	CdTe	0.8	9	20	Y		1.5	48
		CIS		11				2.8	95
		mc-Si		14				5.5–2.4–2.5	167–72–57
Pacca et al.	2007	PVL 136 a-Si	1	6.3		Y	5.7	3.27.5	34.3
		KC 120 mc-Si		12.92			2.7		72.4
Roes et al.	2007	Polymer	0.8	5	25			0.93	727

a-Si – Amorphous, sc-Si – Single/mono-crystalline, mc-Si – Multi/poly crystalline.

The end-of-life management has negligible environmental burdens and is neglected in preliminary studies. However Wambach et al. [1] indicate a reduction of the energy pay-back time (EPB-T) by half when using recyclable material for wafer-based solar modules. Comparison between PV studies is difficult since investigations employ different methods, use various data sources, replace unknown data with similar ones and take into account different levels of irradiation, operational periods and other assumptions for future technology enhancement.

This paper investigates the environmental concerns of emerging PV technologies regarding the hybrid QD-based solar cells under development. In addition, sustainability criteria results (*EPB-T*, greenhouse gas *GHG* emissions and net energy ratio *NET*) are compared with previous thin-film LCA studies. At the same time initial characteristics, such as minimum viable efficiencies and lifetimes, for hybrid QD-based solar cells as a sustainable energy source are suggested.

2. Assumptions and boundaries

The study investigated new designs for low cost solar cells under development within a consortium between the University of Manchester and Imperial College London. The aim of the project is to develop affordable hybrid QD-based solar cells for use in PV micro-generator systems for deployment in the UK and worldwide [2].

For conventional PV technologies 80% of the initial efficiency is usually guaranteed up to 25 years. Most LCA studies have neglected efficiency degradation and different lifetime periods (15, 20, 25 and 30 years) were considered. These assumptions influence the lifetime energy generation and thereby the NER. On the other hand Krebs and Spanggaard [3] define polymer solar cell lifetime as the time it takes for the efficiency to decay to half its initial value. Therefore for easy comparability the initial analysis assumes 10% conversion efficiency without degradation and 25 years lifetime as shown in Table 2. Lower conversion efficiencies, and shorter lifetimes are discussed further in this paper.

For the purpose of this study a 1 cm^2 substrate laboratory-scale production was considered. The main input flows of the inventory shown in Table 3 were based and modelled on the available datasets from Ecoinvent version 2.01 [4]. Parallel analyses of two

Table 2
Comparable assumed characteristics for future hybrid solar cells.

Solar Cells	η (%)	cm^2/Wp	Lifetime	Reference
Hybrid QD-based	10.0	100	25 assumed	Project
Polymer	05.0	200	25 assumed	Konarka (2004)
Dye Sensitised	08.0	125		Veltkamp et al. (2006)
Mono-crystalline	13.2	076	30	Alsema et al. (2006)
Thin-film (CdTe)	09.0	111	20	Raugei et al. (2007)
Thin-film (CIS)	11.0	091	20	Raugei et al. (2007)

Table 3
Main input inventory flows for hybrid QD-based solar cells production.

	Blend type	Varient type
Glass	0.7737 g/cm^2	0.7737 g/cm^2
ITO	1.15E-04 g/cm^2	1.15E-04 g/cm^2
PEDOT:PSS	4.32E-04 g/cm^2	
Polymer	1.11E-04 g/cm^2	1.11 E-04 g/cm^2
QD	1.11 E-04 g/cm^2	6.71 E-05 g/cm^2
Solvents	8.85E-05 g/cm^2	8.85E-05 g/cm^2
Inorganic nanoparticles		4.54E-03 g/cm^2
Al	5.10E-06 g/cm^2	
Gold		3.65E-05 g/cm^2
PVDC	0.0133 g/cm^2	0.0133 g/cm^2
PET	0.0133 g/cm^2	0.0133 g/cm^2
Electricity	0.01 kWh/cm^2	0.01 kWh/cm^2

types: variant and blend type solar cells were performed and compared to conventional crystalline and amorphous PV technologies.

The assembly of the solar cell module is based on previous thin-film fabrication processes. The process energy required is assumed to be 100 kWh/m^2 of solar cell area as extrapolated from laboratory processes. This is consistent with Greijer et al. [5];Alsema [6];Brummelen and Nieuwlaar [7]. The energy mix considered is based on the European Union for Co-ordination of Transmission of Electricity system which includes coal, gas, oil, nuclear, hydro, biomass and wind energy.

The initial analysis considered the average southern European yearly radiation (1700 kWh/m^2) which was chosen as a common basis for comparability with other LCA studies. The amount of solar radiation absorbed by a PV system establishes the annual electricity output (AEO). PV system losses due to balance of system components (BOS) and other indirect losses were assumed at 25% (performance ratio PR = 0.75). This ratio, which ranged from 0.65 to 0.95 in previous LCA studies, is taken for easy comparability.

Some PV LCA studies have omitted BOS. Keoleian and Lewis [8] argue that if the scope of the analysis is to evaluate the total energy requirements for electricity generation and delivery to the point of use, then the product system would also include the additional components needed to connect the PV module to electricity transmission lines ('the grid') and from the grid to a building's junction box. The solar cell inventory assumes frameless modules as hybrid solar cells are likely to be manufactured as building integrated products. However since glass substrate is considered for this study, aluminium frames and support steel structure are included. Though BOS for building integrated PV (BIPV) may differ from structured PV systems due to the integration aspect, the inventory of a typical BOS for a grid-connected rooftop installation is applied to the analysis and the main components are listed in Table 4 from Raugei et al. [9].

End-of-life management and recycling alternatives were not included due to lack of data for similar type of solar cell. However, such investigations may assume that glass and metals are recycled offering reduction of mineral resources, inorganic substances are disposed in landfills potentially offering energy recovery and the rest of polymers are incinerated.

Table 4
Inventory of main input flows to the BOS per m^2 of PV area.

Al (frame)	1900 g/m^2
Steel (support structure)	25000 g/m^2
Cu (cables and contact boxes)	40 g/m^2
Plastics (cables and contact boxes)	40 g/m^2
Fuel oil (for installation)	10.8 MJ/m^2

3. Methodology

The LCA was performed in accordance with EN ISO14040 and updates [10], which is divided into 4 steps: goal and scope definition, inventory analysis, impact assessment and interpretation.

The LCA methodology offers an excellent foundation for conducting other analyses such as life cycle energy analysis (LCEA) and life cycle costing analysis (LCCA) where the results are compared and integrated in the evaluation. The OpenLCA version 1 open source tool [11] was used.

Two impact assessment methods were used to access the potential impacts of the environmental flows collected in the inventory stage. The GHG emissions are evaluated with Intergovernmental Panel on Climate Change (IPCC) 2001 data for a timeframe of 100 years, while the Cumulative Energy Demand (CED) is calculated by the method described in Ecoinvent 1.01 by summing all fossil, nuclear, hydro and renewable energy demand into one single CED value [12].

Significant parameters for LCA interpretation of PV systems and other renewable energy production technologies are the NER, the EPB-T and GHG emissions per unit generated. The latter is the calculation of the total emitted GHGs during a system's life cycle divided by the electricity generated over the lifetime. The EPB-T determines the amount of years needed so that the system compensates for the energy during production. Though this metric does not take into account differences in the type of energy (e.g. nuclear or fossil) or quality differences (e.g. electricity or heat use). Jungbluth et al. [13] describes EPB-T as the time until environmental impacts from the production of the plant have been levelled out due to avoidance of resource use and/or emissions of a conventional reference system that produces the same amount of electricity. The system NER described by Pacca et al. [14] or the electricity production efficiency referred to by Keoleian and Lewis [8] compares the total life cycle energy inputs with outputs; that is the life cycle energy output (LCEout) over its life cycle energy input (LCEin), which stipulate the renewable energy obtained from each energy input source (most likely to be from fossil fuels). Despite the specific PV technology, these three weights/metrics are strongly affected by the model being used for irradiation level, orientation, energy for fabrication, system performance, system lifetime and system design.

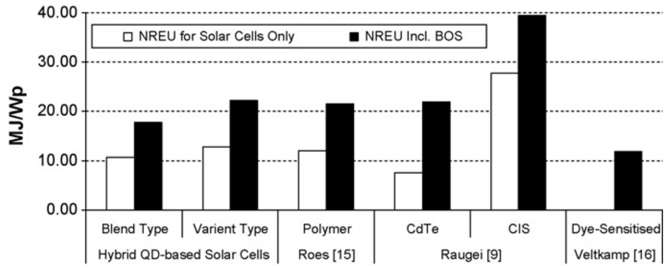
Keoleian and Lewis [8] states that NER should be the metric of choice when comparing electricity-generating systems. The maximum electricity production efficiency of a PV system is a function of its useful life, so this metric may evaluate the lifetime energy performance of an electricity-generating system.

4. Results

The initial calculated impact indicators for the analysed PV systems using hybrid QD-based solar cells under development are presented in Figs. 1–4 along with comparable previous thin-film PV technologies LCA studies. Table 5 summarises the results and evaluations of the environmental boundaries. These are the initial results of hybrid QD-based solar cell technologies using available datasets. Therefore the results may be subject to change in the future as technology matures and more datasets become available.

5. Interpretation and discussion of results

From the life cycle impact assessment (LCIA) results, hybrid QD-based solar cells compare favourably with other new thin-film PV technologies. The very small amounts of chemical compounds required contribute to low environmental impacts. It has been confirmed through sensitivity analysis that no specific chemical



NREU- Non-Renewable Energy Use

Fig. 1. Gross energy requirement.

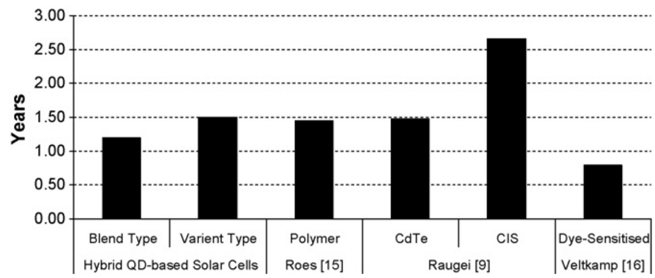


Fig. 2. Energy pay-back time (EPB-T).

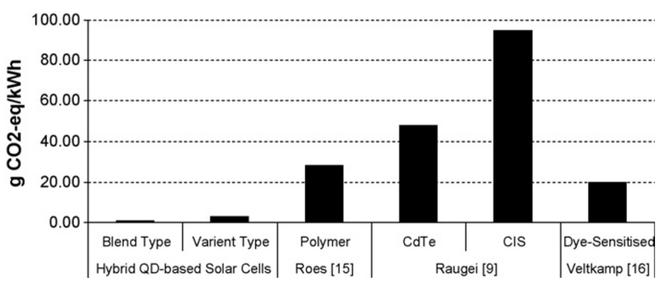


Fig. 3. Global warming potential (GWP).

contributes more than 20% of the overall impact indicator. This is consistent with Raugei et al. [9]. The process energy was the main contributor for non-renewable energy use (NREU) and global warming potential (GWP) impacts. An extrapolated laboratory-scale production to commercial production may reduce this burden given that laboratory-scale processes tend to be less efficient than commercial processes. The BOS contributes nearly to half the energy required of a PV system having hybrid QD-based solar cells. Since glass substrates were considered in this study, module frames and support structures had to be included.

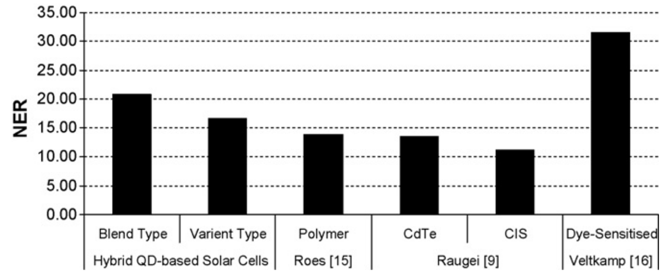


Fig. 4. Net energy ratio (NER).

Table 5
Summary of results and PV technology comparison.

	Hybrid QD-based Solar Cells	
	Blend type	Varient type
Assumptions and Boundaries		
H	1700 kWh/m^2	1700 kWh/m^2
PR	0.75	0.75
Efficiency	10%	10%
Area	100 cm^2/Wp	100 cm^2/Wp
Lifetime	25 years	25 years
Calculations		
Yearly generation	1.28 kWh/Wp	1.28 kWh/Wp
Energy output	31.88 kWh/Wp	31.88 kWh/Wp
Yearly energy output	14.79 MJ/Wp	14.79 MJ/Wp
Energy output	369.75 MJ/Wp	369.75 MJ/Wp
Impacts		
NREU for solar cells only	12.64 MJ/Wp	12.64 MJ/Wp
NREU Incl. BOS	17.7594 MJ/Wp	22.19 MJ/Wp
Climate change	35.34 g CO_2-eq/Wp	92.03 g CO_2-eq/Wp
Evaluation		
Climate change	2.89 gCO_2-eq/kWh	2.89 g CO_2-eq/kWh
E-PBT	1.51 years	1.51 years
NER	20.82	16.66

However the impact associated with BOS can be reduced significantly by using BIPV systems and other substrates.

The hybrid QD-based solar cells are a sustainable alternative for electricity generation within the PV technology arena and may have the potential to generate more than 10 times the amount of energy received during production. All assumptions and boundaries taken may be considered as reasonable estimates for commercialisation of hybrid QD-based solar cells. However the main uncertainties are the electrical energy used in the solar cell production process and the lifetime as well as performance of these future PV systems. Hence further detailed LCA studies extrapolated to commercial scale production will be required in the future to minimise uncertainties.

Table 6
NER sensitivity analysis for variant type hybrid QD-based solar cell.

η (%)	Lifetime (Yr)									
	1	2	3	4	5	6	7	8	9	10
1	0.07	0.13	0.20	0.27	0.33	0.40	0.47	0.53	0.60	0.67
2	0.13	0.27	0.40	0.53	0.67	0.80	0.93	1.07	1.20	1.33
3	0.20	0.40	0.60	0.80	1.00	2.00	1.40	1.60	1.80	2.00
4	0.27	0.53	0.80	1.07	1.33	1.60	1.87	2.13	2.40	2.67
5	0.33	0.67	1.00	1.33	1.67	2.00	2.33	2.67	3.00	3.33
6	0.40	0.80	1.20	1.60	2.0	2.40	2.80	3.20	3.60	4.00
7	0.47	0.93	1.40	1.87	2.33	2.80	3.27	3.73	4.20	4.67
8	0.53	1.07	1.60	2.13	2.67	3.20	3.73	4.27	4.80	5.33
9	0.60	1.20	1.80	2.40	3.00	3.60	4.20	4.80	5.40	6.00
10	0.67	1.33	2.00	2.67	3.33	4.00	4.67	5.33	6.00	6.67

Table 7
CO_2-eq/kWh sensitivity analysis for variant type hybrid QD-based solar cell.

η (%)	Lifetime (Yr)									
	1	2	3	4	5	6	7	8	9	10
1	721.80	360.90	240.60	180.45	144.36	120.30	103.11	90.23	80.20	72.18
2	360.90	180.45	120.30	90.23	72.18	60.15	51.56	45.11	40.10	36.09
3	240.60	120.30	80.20	60.15	48.12	40.10	34.37	30.08	26.73	24.06
4	180.45	90.23	60.15	45.11	36.09	30.08	25.78	22.56	20.05	18.05
5	144.36	72.18	48.12	36.09	28.87	24.06	20.62	18.05	14.44	14.44
6	120.30	60.15	40.10	30.08	24.06	20.05	17.19	15.04	13.37	12.03
7	103.11	51.56	34.37	25.78	20.62	17.19	14.73	12.89	11.46	10.31
8	90.23	45.11	30.08	22.56	18.05	15.04	12.89	11.28	10.03	9.02
9	80.20	40.10	26.73	20.05	16.04	13.37	11.46	10.03	8.91	8.02
10	72.18	36.09	24.06	18.05	14.44	12.03	10.31	9.02	8.02	7.22

6. Sensitivity analysis on future PV cell efficiency and lifetime

Low cost solar cells are likely to have shorter lifetimes and lower efficiencies at the initial stage of commercialisation. Sensitivity analysis was performed to assess the impact of variations in efficiency and lifetime on the NER and CO_2-eq/kWh results obtained from the LCA tool. Tables 6 and 7 show the sensitivity analyses for the variant type solar cell.

The results show that shorter lifetimes require a higher efficiency to have an NER value greater than 1. For 1 year lifetime and 1% efficiency, NER is less than 1 and therefore it is not sustainable. If efficiency degradation is considered, the NER values decrease even further. The highlighted area shows sustainability is reached as NER is greater than 1. Similarly the thresholds for efficiency and lifetime with respect to 50 CO_2-eq/kWh are indicated.

7. Conclusion

This paper has provided an initial laboratory-based life cycle analysis on future low cost PV systems using emerging PV technologies such as the hybrid QD-based solar cell. These solar cells are likely to come at the expense of efficiency and durability. Comparable sustainability metrics were calculated and estimated thresholds for efficiency and lifetime related to environmental issues.

On the basis of the data presented in this paper it is shown that future low cost PV systems using hybrid QD-based solar cells are well positioned to compete with other energy technologies. The cost and technical boundaries suggesting future PV systems market integration favourable characteristics with respect to energy price has already been addressed [17–19].

The EPB-T metric is less than half that of crystalline technologies while the CO_2-eq/kWh metric is even less. However, preliminary indications show that lifetimes greater than 1 year and efficiencies greater than 1% are needed for these system to be sustainable. LCA studies are important for low cost PV systems using hybrid QD-based solar cells to penetrate the PV market as another sustainable electricity technology. The focus of this study has been on environmental boundaries for future hybrid QD-based solar cells to be a sustainable source of energy. However in order to ensure robustness of the results further improvements in data quality are needed for emerging PV technologies such as hybrid solar cells.

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